Final Report: Bedforms and Mine Burial in the Nearshore

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LONG-TERM GOAL

The goal of this work is to develop a predictive understanding of coastal bedforms and their effect on the burial of objects on the seafloor.

OBJECTIVES

The objective of the research is to develop a robust characterization of the growth of the bottom profile envelope (the range from minimum to maximum depth) in the nearshore, both in time and space, using existing data. The specific objectives are to

- investigate the time evolution of the bottom profile envelope
- quantify the probability of burial
- develop a model for prediction of bed profile statistics

APPROACH

The generation and migration of bedforms (eg, ripples, megaripples and sand bars) on sandy bottoms in the nearshore (0-8 m water depths) provides a mechanism for objects on the seafloor to become buried. As a bedform migrates past a mine, the mine will fall to the low point of the bedform trough before subsequently being buried by the passage of the following bedform crest. In the absence of other processes (scour and impact burial), the statistics of mine burial by bedforms can be deduced from the statistics of bed elevation changes and the time evolution of the bottom profile envelope. Existing data sets from natural beaches (without objects on the seafloor) are used to examine the bed profile envelope in the nearshore.

We define the bottom profile at a single location as $h(\tau)$, and the profile envelope as spanning from $h_{min}(\tau)$ to $h_{max}(\tau)$. The envelope has zero thickness at $\tau=0$ (eg, when mines are placed) and as bed features form and migrate the envelope grows with time. Maximum bed envelope thickness, D_{max}, at the end of set time windows is calculated (as in Fig 1) and the mean maximum envelope thickness is examined as a function of window length or time (Fig 3) and as a function of location on the beach (Fig 2). In addition, the instantaneous bed elevation above envelope minimum, D=h- h_{min} (Fig 1c), is used to examine the frequency of re-exposure of a buried object on the seafloor for short time scales (days).

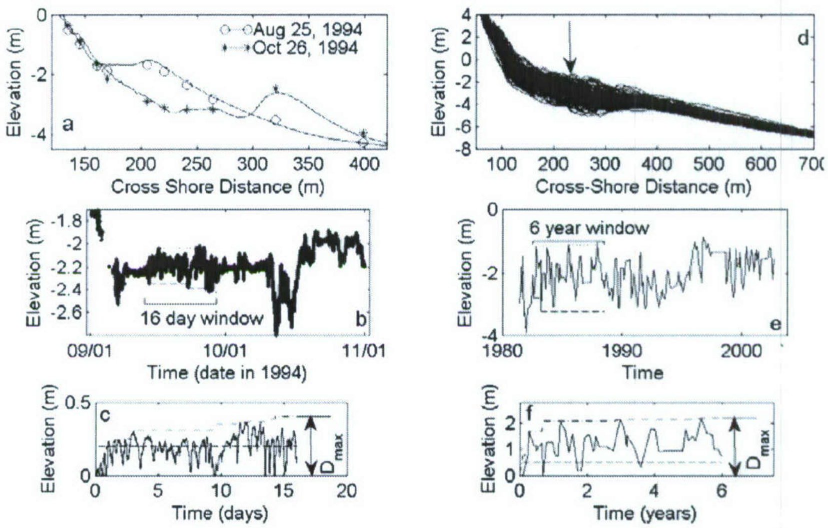

Figure 1 a) Cross-shore profiles (solid lines) and altimeter array (symbols) deployed during Duck94. b) Elevation versus time (solid line) measured with the sonar altimeter at x=170 m in a). The dotted and dashed lines are minimum and maximum depths for a representative 16-day period. c) The dashdot line is the bed profile envelope (the difference between dashed and dotted lines in b) plotted versus time. The solid line is the instantaneous elevation above envelope minimum, D (solid line minus dashed line in b). The dashed line in c) is an example elevation threshold, W, eg the height of a mine. d) Cross-shore profiles 1981 through 2002, Duck, NC. e) Time series of bed elevation at X = 225 m in d) sampled from approximately monthly profiles and averaged over 20 m in the cross-shore. The dashed and dotted lines represent the maximum and minimum depths reached during a representative 6-year period. f) The bed profile envelope (the difference between dashed and dotted lines in e), plotted versus time (dashdot). The solid line is the instantaneous elevation above envelope minimum, D (solid line minus dashed line in e).

This study is based on a number of different data sets. Time series of bed elevation from sonar altimeters deployed during the Duck94 Nearshore Field Experiment resolve megaripple migration and 2-3 bar migration events over a 2 month period (Gallagher et al. 1998). Longer-term surveying campaigns from Duck, NC, Egmond aan Zee, The Netherlands (Ruessink et al. 2003) and Hasaki, Japan (Kuriyama 2002) are lower in temporal resolution but capture complete bar migration cycles (years). Together these data sets (Table 1) provide a comprehensive look at bed changes in the nearshore.

WORK COMPLETED

Mean D_{max} has been examined as a function of both cross-shore position (Fig 2) and time (Fig 3) using all data sets. An exponential taper model is presented that represents the observations of the growth of

D_{max}. Frequency of burial, B, has been investigated for short time scales (days) using high temporal resolution data from Duck94 (Fig 4). These results are discussed herein.

Table 1: Information on data sets used for envelope study.

	Region included	Duration	Sample freq.	Mean annual Hsig (m)	Beach slope	Grain Size (mm)	x_{shore} d_{shore} (m)	x_{sea} d_{sea} (m)
Duck94 altimeters	Surf	2 mos	1/32s	1.1	1/70	0.12-0.3	100 1.4	375 -3.85
Duck survey	Surf offshore	~22 yrs	1/mon	1.1	1/70	0.12-0.3	100 1.4	375 -3.85
Egmond survey	Surf offshore	~40 yrs	1/yr	1.2	1/120	0.25-0.35	75 -1	675 -6
Hasaki survey	Surf	~8 yrs	1/day	1.5	1/60	0.18	50 0	415 -5.5

In the absence of storm waves, the growth of D_{max} primarily is owing to the migration of megaripples. Under these conditions the D_{max} grows to a maximum of about 40-50 cm after 8 days. This envelope growth under moderate conditions is correlated to significant wave height. After storm waves (significant wave height > ~1m) have occurred, larger scale changes dominate the growth of the bed envelope and the correlation with wave height is diminished (not shown).

A manuscript describing all this work is in press in the Mine Burial Special Issue of Journal of Oceanic Engineering.

RESULTS

Envelope thickness grows largest and most rapidly inside the surf zone (the seaward and shoreward extent of the surf zone and their corresponding depths are given by x_{sea}, x_{shore}, d_{sea}, d_{shore}, see Table 1) (Fig 2). Further offshore the envelopes are smaller and growth occurs much more slowly. This is owing to the high energy of wave shoaling, wave breaking , strong currents and turbulence, and resulting high rates of sediment transport in the shallow surf zone. Following the work of Ruessink et al. 2003, the envelopes in Fig 2 a, c, and e were normalized by maximum envelope thickness and the cross shore position was normalized by the depths at the shoreward and seaward extent of the surf zone (Table 1), so that the different beaches could be compared (Fig 2 b, d, and f). Similar to the observations of Ruessink et al. 2003, the maximum amplitude of the envelope is close to the seaward extent of the surf zone and the amplitude of the envelope drops quickly outside the surf zone (normalized depth > 1).

To examine the growth of envelopes in time, the cross-shore D_{max} profiles (Fig 2) were averaged over two regions: the surf zone and the offshore region (Table 1). The surf zone was averaged from the shoreline (x_{shore}) to a location that corresponds to the outer extent of bar activity (x_{sea}). Ruessink et al 2003 determined this position quantitatively. Here, beach profiles were examined and a suitable location was chosen, eg, in Fig 1d, it is quite clear where bar migration activity ends (x=415m). Thus, for the present purposes, the surf zone is defined by the morphology. This separation is reasonable because these two regions are dominated by significantly different processes: breaking, turbulence and strong wave-driven currents in the surf zone versus shoaling oscillatory flows, wind and tidally driven currents offshore.

The time scale of the growth of the bed envelope is quite long (~2 years for Hasaki, ~6 years for Duck and ~12 years for Egmond; Fig 3) for the surf zone data (and even longer for the offshore data). One explanation is the duration of bar migration cycles (Ruessink et al. 2003, Wijnberg and Terwindt 1995), where bars are observed to be generated at the shoreline, migrate offshore over the course of many years and decay at the outer edge of the surf zone. Envelope growth owing to bar migration at any location within the surf zone would be expected to reach equillibrium only after at least one full cycle of offshore bar migration. Ruessink et al. (2003) found that the bars at Egmond evolved and migrated more slowly than those at Duck. Similarly, here the Egmond envelopes (triangles) grow more slowly than Duck (circles) and both grow much more slowly than the Hasaki envelopes (squares). In Fig 3c, the time axis is normalized by the bar cycle durations for the different beaches and the growth curves almost collapse together.

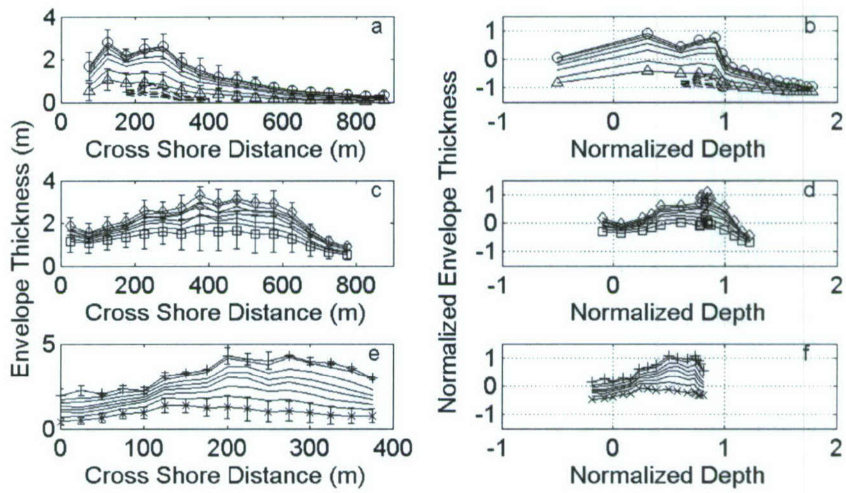

Figure 2. Maximum envelope thickness, D_{max}, plotted versus cross-shore position (a, c and e) and normalized D_{max} plotted versus normalized depth (b, d and f) for different time windows. a&b) Duck long term survey data with windows of 0.5 (triangles), 1, 2, 3, 4, 5 and 6(circles) years. D_{max} and normalized D_{max} curves from Duck94 are shown as dashed lines in panels a and b. c&d) Egmond survey data with windows of 4(squares), 5, 6, 7, 8, 9, 10, and 12(diamonds) years. e&f) Hasaki survey data with windows of 30 days (x), 50 days, 70 days, 0.5, 0.7, 1, 2, and 3 years (pluses). [All envelopes show largest and most rapid growth in the surf zone. In the midst of the surf zone D_{max} grows to almost 5m after 3 yrs at Hasaki, almost 4m after 12 yrs at Egmond and 3m after 6 yrs at Duck.]

It was proposed as part of this study that the growth of D_{max} with time would follow an exponential taper (increase quickly at first and then taper off to a maximum asymptotic value). This trend is seen in Fig 3. The dash line in Figure 3b represents an exponential taper model fit to the surf zone data (open symbols and asterisks) from the equation

$$D_{max\_pred}=b_1\{1-\exp[-b_2(t_n-t_1)]\}-b_3$$

where t is time and b_1=1.33, b_2=7.38 and b_3=1 are the fit parameters. Because the envelope represents the depth of bed that is disturbed by the migration of bedforms, D_{max_pred} can be considered a maximal depth to which objects on the seafloor might be buried inside the surf zone. The model coefficients for the fit to the offshore data (closed symbols and dotted line in Fig 3b) are b_1=0.87, b_2=0.22 and b_3=1.18. The model coefficients fot the data normalized by bar cycle length are b_1=1.42, b_2=3.09 and b_3=0.81 (dashed line Fig 3c). If bar cycle duration is known, the model in Fig 3c can predict maximum burial depth. However, for beaches with unknown bar cycle durations (which is a parameter that is difficult to obtain and highly variable from one site to the next), the curves in Fig 3b may be used for prediction of object burial with sensible assumptions about the magnitude of the maximum envelope fluctuations (3-4 m for the beaches studied). Thus, the curves in Fig 3 can be used to predict the maximum burial depth as a function of time. Interestingly, no information regarding hydrodynamic forcing is needed to make these curves almost collapse together.

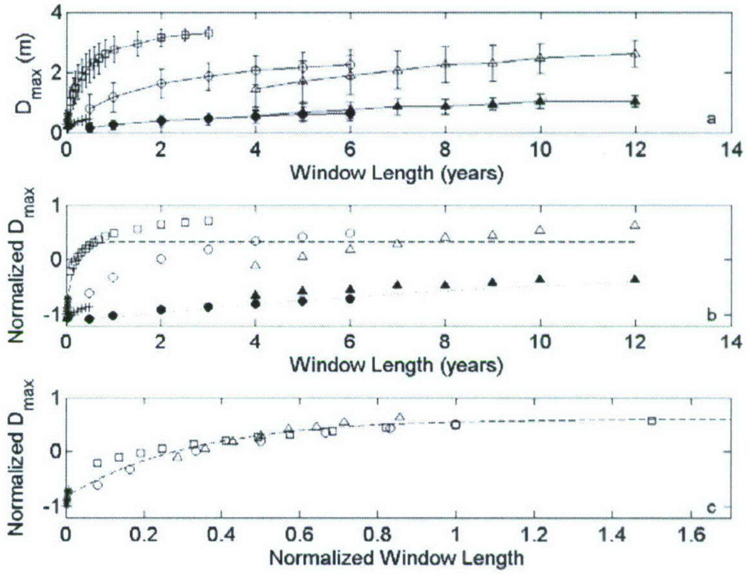

Figure 3. a) Mean (and standard deviation of) D_{max}, for the long-term survey data sets (Duck-circles, Egmond-triangles, Hasaki-squares) plotted versus time. Open symbols are averages from the surf zone, filled symbols are averages of offshore data. b) Normalized mean D_{max} (symbols same as in a) plotted versus time. Dashed line is exponential taper fit to surf zone data (open symbols and asterisks). Dotted line is exponential taper fit to offshore data (filled symbols and pluses). c) Normalized mean D_{max} (symbols same as in a) from the surf zone plotted versus window length normalized by the bar cycle duration for each data set. Dashed line is exponential taper fit to all data. [Curves (although varied) increase as an exponential taper, quickly at first and approaching an asymtotic value. Surf zone curves grow quickly to about 3 m after 4-12 years. Curves representing offshore data grow slowly, reaching about 0.5 m after 12 years.] Asterisks are mean D_{max} from the short-term altimeter and pluses are mean D_{max} from the bipod altimeters in deeper water at Duck, NC.

Mean D_{max} is a statistical measure of the amplitude of bed motion and the maximum possible burial. However, at any given time, burial depends on the instantaneous elevation of the bed relative to the object. For example, an object that has fallen to a bedform trough can be buried by a bedform crest. D_{max} is now larger than the object. Although D_{max} remains the same or continues to grow (eg, dashdot line in Fig 1c and 1f), subsequent re-exposure of the object in the next trough of the migrating bedform is possible. The likelihood of burial or exposure after a set amount of time was examined (Fig 4) over short time scales (days) using the high resolution Duck94 data.

To investigate the likelihood of burial of an object, we assumed that an object always falls to h_{min}, the lowest elevation possible. Then the instantaneous elevation of the bed above envelope minimum, $D = h - h_{min}$ (solid line in Fig 1c) was compared to a threshold elevation W (the vertical scale of the object, dotted line in Fig 1c) at the end of the set time windows. If D>W then an object was buried and if D<W then an object was exposed. Time windows were moved in 1 hr increments, thus hourly measures of "buried/not buried after X days" were obtained. Frequency of burial, B, was calculated as the number of buried observations divided by the total number of observations (Fig 4).

B is observed to increase with time and B is higher shallow water (Fig 4). For example, at x=240 m (Fig 4) there was significant erosion/accretion owing to bar migration during Duck94, thus an object on the seafloor in this region would become more deeply buried than at x>320 m. A 15cm-high object would be buried more than 50% of the time after only 6 days (star in Fig 4a). In deeper water, less energy reaches the seafloor, so D_{max} (Fig 2) and B are smaller and grow more slowly. A 15 cm-high object would be buried less than 25% of the time at x-400 m.

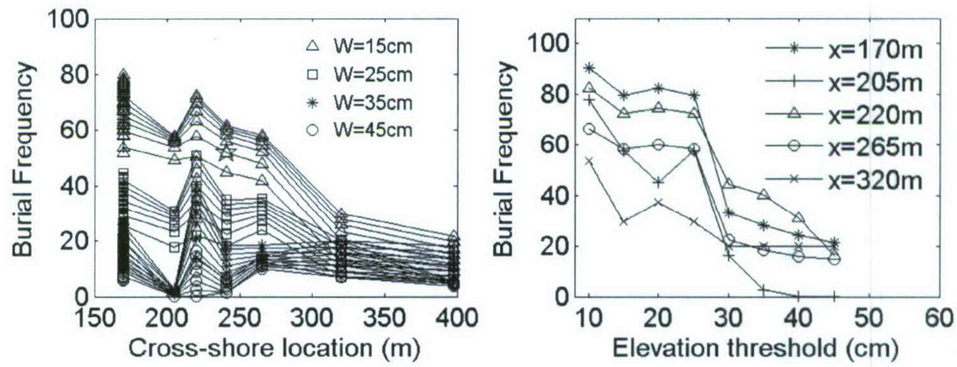

Figure 4. a) Burial frequency, B, versus cross-shore location, for 4 different values of W. Each group of curves represents 4-16 day windows with B increasing with window length. b) Burial frequency, B, versus elevation threshold, W, for different cross-shore locations. [a) B increases with time window (within each group of curves) and is higher in shallow water. For a 25 cm object in the surf zone (squares at x=220m), B=25% after 4days and 40% after 16 days. Outside the surf zone, B=5-20%.]

This result is for the beach at Duck, NC and it is clear from Fig 3 that different beaches respond to incoming waves at different rates. However, the overall observation is consistent: as waves work the sediments on the seafloor, megaripples are generated and migrate, erosion and accretion take place and both D_{max} (Figs 2 and 3) and B increase (Fig 4). In the surf zone, waves break, currents are strong, and more energy is available to move sediment than further offshore, therefore morphological processes occur more quickly. This is reflected in the growth of the bed envelope and the resulting likelihood of burial which is larger and faster inside the surf zone than further offshore. The growth of the envelope is represented by an exponential taper model, growing quickly at first and slowly approaching an asymptotic value. This model could be used to predict maximal burial depths in the nearshore.

IMPACT/APPLICATION

The threat of mines has an enormous impact on Naval operations. Methods exist for search and identification of proud mines, but the potential existance of buried mines is of considerable concern. This work will help to describe the process of mine burial owing to bottom bedform movement by quantifying the expected time scales and depths of disturbance of the natural bed in the nearshore.

TRANSITIONS

This work has not yet lead to any transitions.

RELATED PROJECTS

This work is part of the Mine Burial Program, a coordinated effort to study all processes of mine burial including impact and scour burial.

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PUBLICATIONS

Abstracts and Presentations
Gallagher, E.L. and R.A. Holman, Jan. 2004. Bedform Migration and Bed Envelope Statistics. Abstract presented at the American Geophysical Union Ocean Sciences Meeting, Portland, OR.

Gallagher, E.L. and R.A. Holman, Dec. 2004. Bedform Migration and Bed Envelope Statistics. Abstract presented at the American Geophysical Union Fall Meeting, San Francisco, CA.

Peer-reviewer publications
Gallagher, E.L., E.B. Thornton and T.P. Stanton (2003) Sand bed roughness in the nearshore, *J. Geophysical Research*, 108(C2), 3039. [published, refereed]

Gallagher, E.L. (2003) A note on megaripples in the surf zone: evidence for their relation to steady flow dunes, *Marine Geology*, 193, 171-176. [published, refereed]

Gallagher, E.L., R.A. Holman, and E.B. Thornton, 2006. Evolution of the nearshore bed envelope. Submitted: *Journal of Oceanic Engineering*, Mine Burial Special Issue. [in press, refereed]

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14. ABSTRACT
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As waves work the sediments on the seafloor, megaripples are generated and migrate, erosion and accretion take place. These motions cause objects on the seafloor to become buried. In the surf zone, waves break, currents are strong, and more energy is available to move sediment than further offshore, therefore morphological processes occur more quickly. This is reflected in the growth of the envelope of seafloor motions and the resulting likelihood of burial, which is larger and faster inside the surf zone than further offshore. The growth of the bed envelope is represented by an exponential taper model, growing quickly at first and slowly approaching an asymptotic value. This model could be used to predict maximal burial depths in the nearshore.

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